6. WHAT WE DO NOT KNOW AND PROBABLY NEED TO KNOW
6.1 About problems identified during Apollo

By far the most important data-base to help us determine the engineering questions we need to address comes from the Apollo experience. In combing through the Apollo Mission Reports and Technical Debriefings there are numerous references to the problems caused by lunar dust during the missions. These have been sorted into nine classes of difficulties.[1]

6.1.1 Vision Obscuration and False Instrument Readings

The first dust-related problem experienced by the Apollo astronauts occurred when they landed the Lunar Module (LM). The Apollo 11 crew reported that "Surface obscuration caused by blowing dust was apparent at 100 feet and became increasingly severe as the altitude decreased." This was even more of a problem for Apollo 12 where there was total obscuration in the last seconds before touchdown to the extent that there was concern that one of the landing feet could have landed on a boulder or in a small crater. In Apollo 14 the landing profile was adjusted to be more steep, and the astronauts reported little difficulty in seeing the landing site. However, this may have been due in part to the Apollo 14 landing site being intrinsically less dusty, because Apollo 15 and Apollo 16 also used the steeper landing profile, and both reported difficulties seeing the landing site in the critical last seconds. Apollo 17 experienced some vision obscuration in the landing of the LM, but they were able to see boulders and craters through the blowing dust all the way to touch down.

The Apollo experience reveals that the extent that vision obscuration as a problem on landing is dependent on the amount of loose dust in the specific landing zone. The record has far fewer references to dust-related problems in Apollo 14 and 17, where there was little obscuration on landing, than in those of the other missions. Thus, the amount of loose dust will probably remain a variable as long as spacecraft are landing in unexplored territory. Since vision obscuration is dependent on the depth of loose dust in a particular area, crews may use this as an indicator of how much difficulty they can expect to have with dust during EVA activities.

In addition to vision obscuration on landing, the dust caused minor problems with photography. The Apollo 15 crew reported problems with a halo effect on the television camera transmission. This was remedied by brushing the dust off of the lens.

In Apollo 12 the landing velocity trackers gave false readings when they locked onto moving dust and debris during descent. The Apollo 15 crew also noted that landing radar outputs were affected at an altitude of about 30 feet by moving dust and debris. But the Apollo 17 crew reported no lock-up onto moving dust or debris near the lunar surface. This again points out the differences in the amount of dust at the different landing sites, with it being higher at the Apollo 12 and 15 sites, and lower at the Apollo 17 site.

Vision obscuration and false instrument reading point out the need to better understand dust transport processes. There has been a great deal written about the elevation of dust at the day/night terminator passage. The solar wind along with solar flares and solar storms give rise to a negatively charged plasma over the entire surface of the moon. Electric charges as high as thousand of volts may build up on the night side. On the day side, the intense solar ultraviolet light removes electrons by the photoelectric effect giving dust grains a net positive charge. At the terminator positively charged dust grains may be pulled over to the negatively charged regolith, the result being a churning of the upper dust layers. There is controversy about the magnitude of the effect, and whether it will have consequences for the lunar outpost.

Relatively little work has gone into the dust transport that will occur under landing and launch conditions, even though this importance of this effect is beyond doubt. Recent analysis of the videotape of Apollo landings has determined that regolith particles are ejected away from the landing site at tremendous speed.[2] The possibility of an orbiting debris cloud that could bombard the landing site over and over as its elliptical orbit grazes the lunar surface has even been suggested.

In addition to dust transport, there is also a need to better understand the light scattering properties of the dust both in the visible and in the radar wavelengths. Light scattering is a well-developed theory with inputs including particle size and dielectric constant. But the Apollo experience again cautions that there will be site-to-site variation in the particle size distributions. And there may be substantial differences in the dielectric constant of the soil in polar regions if it contains an appreciable amount of water ice.

6.1.2   Dust Coating, Contamination, Clogging, and Loss of Traction

Dust was found to quickly and effectively coat all surfaces it came into contact with, including boots, gloves, suit legs and hand tools. Consequences included the Apollo 11 astronauts repeatedly tripping over the ~~dust~~ dust-covered TV cable, and a contrast chart on Apollo 12 becoming unusable after being dropped in the dust. This was particularly troublesome on Apollo 16 and 17 when rear fender extensions were knocked off of the Lunar Roving Vehicle (LRV) and dust "rooster tailed" and showered down on top of the astronauts. Dust coating is the precursor to other problems such as clogging of mechanisms, seal failures, abrasion, and the compromising of thermal control surfaces. In addition, valuable astronaut time was spent in ordinary housekeeping chores like brushing off and wiping down equipment – which often proved ineffective.

Neil Armstrong reported material adhering to his boot soles caused some tendency to slip on the ladder during ingress back to the LM. However, this slipperiness was not reported by any of the other crew members, and there are specific references in the Apollo 12 record that this was not a problem for them. It became standard practice for the astronauts to kick the excess dust off of their boots on the ladder before they re-entered the LM in an attempt to keep as much dust as possible out of the spacecraft, and it is likely that this measure was enough to keep slipping from happening.

Although there was concern about the surface being slippery, there are no incidences in the mission record of falling due to slips, though some of the astronauts tripped and fell. In the Apollo experience, loss of foot traction was not a major concern, as long as simple precautions and care were used.

There were reports of equipment being clogged and mechanisms jammed in every Apollo mission. These included the equipment conveyor, lock buttons, camera equipment, and even the vacuum cleaner designed to clean off the dust. Dust made Velcro® fasteners inoperable, and was a particular problem with some LRV indicator mechanisms. The dust also clogged spacesuit (or as they were called during Apollo, Extravehicular Mobility Unit or EMU) mechanisms including zippers, wrist and hose locks, faceplates, and sunshades.

The most alarming characteristic was how quickly and irreversibly this could happen. One short ride on the LRV with a missing fender extension, or momentary standing where the equipment conveyor dumped dust on the EMU began difficulties immediately. With Apollo EMU and

equipment designs there was very little room for error. All of the astronauts experienced difficulties to some degree, even those with the shortest stays on the surface. Several remarked that they could not have sustained surface activity much longer or clogged joints would have frozen up completely.

Understanding dust transport properties will again be key to controlling dust coating and contamination. Probably the most important processes will be the dust transport by human activities. The Apollo astronauts time and again were frustrated because they accidentally kicked dust onto surfaces, and then had trouble removing it. As noted above, rovers have a particularly high potential to elevate dust.

Dust adhesion will be the controlling factor for coating and contamination. The adhesive forces were found to be surprisingly high. It was difficult to remove the dust which seemed to be everywhere. Related to the dust adhesion is very high dust cohesion. The slipping the Armstrong noted was a combined result of dust adhesion and cohesion.

6.1.3 Thermal Control Problems[3]

A surface layer of dust on radiator surfaces could not be removed and caused serious thermal control problems. On Apollo 12, temperatures measured at five different locations in the magnetometer were approximately 68 °F higher than expected because of lunar dust on the thermal control surfaces. Similarly, on Apollo 16 and 17 the LRV batteries exceeded operational temperature limits because of dust accumulation and the inability to effectively brush off the dust. John Young remarked that he regretted the amount of time spent during Apollo 16 trying to brush the dust off of the batteries – an effort that was largely ineffective. (This was contrary to ground-based tests which indicated that dusting the radiator surfaces would be highly effective.) This led him to recently remark that "Dust is the number one concern in returning to the moon." In addition to difficulties with communications equipment and TV cameras, some of the instruments on both Apollo 16 and 17 had their performance degraded by overheating due to dust interfering with radiators.

The effect of dust on thermal control surfaces starts with dust transport to the thermal control surface. If the large power system radiator placement is high off of the surface (≈ 10 m) then dust elevated by the passing of the terminator or being kicked up by astronauts or their rovers can be minimized. However, those astronauts and their rovers themselves have thermal control surfaces which must be protected. For mitigation techniques the adhesion and cohesion of the dust must be understood in order to develop effective dust mitigation strategies. Given that it is unlikely that the radiators will remain perfectly clean, the thermal optical properties, absorptivity and emissivity of thermal control surfaces partially covered with dust will be required as well. In addition, if a significant layer of soil builds up on the thermal control surface, the bulk thermal conductivity could affect performance as well.

6.1.4 Abrasion

Lunar dust also proved to be particularly abrasive. Pete Conrad noted that the suits were more worn after 8 hours of surface activity that their training suits were after 100 hours and further reported that their EMU were worn through the outer layer and into the Mylar® multi-layer insulation above the boot. Gauge dials were so scratched up during the Apollo 16 mission as to be unreadable. Harrison Schmitt's sun shade on his face plate was so scratched that he could not see out in certain directions. Clearly, if the mission time is to be extended to months on the surface, these abrasion problems must be solved.

Abrasivity is, of course, the important parameter here. Abrasion is dependant on the material the regolith comes in contact with. Dust transport is again an issue, and most of the time adhesion and cohesion are as well, ~~though loose~~though loose regolith can act as an abradant as well.

6.1.5   Seal Failures

The ability of the EMU to be resealed after EVA was also compromised by dust on the suit seals. The Apollo 12 astronauts experienced higher than normal suit pressure decay due to dust in fittings. Pete Conrad's suit, which was tight before the first EVA, developed a leak rate of 0.15 psi/min after it, and rose to 0.25 psi/min after the second EVA. Since the safety limit was set at 0.30 psi/min, it is doubtful whether a third EVA could have been performed, had it been scheduled. Another indicator of the difficulty making seals in the dusty lunar surface is that all of the environmental sample and gas sample seals failed because of dust. By the time they reached earth the samples were so contaminated as to be worthless.

This does not bode well for a long duration habitat where several astronauts will be passing through air locks and unsealing and resealing their EMU routinely. More attention must be directed at ways either to keep dust off of the seals, or to make more dust tolerant seals. The important properties to understand to mitigate against seal failures are adhesion, and abrasion.

6.1.6   Inhalation and Irritation

Perhaps the most alarming possibility is the compromising of astronaut health by irritation and inhalation of lunar dust. The Apollo crews reported that the dust gave off a distinctive, pungent odor, (David Scott suggested it smelled a bit like gun powder) suggesting that there are reactive volatiles on the surface of the dust particles. Dust found its way into even the smallest openings, and when the Apollo 12 crew stripped off their clothes on the way back to earth, they found that they were covered with it. Dust was also transferred to the Command Module during Apollo 12 and was an eye and lung irritant during the entire trip back. Given the toxicity of particle sizes less than about 5 μm, this points out the need to monitor the concentrations of dust particles within the EMU, the airlock, the habitat, and the spacecraft.

Later Apollo missions were more cognizant of the problem, and dust management strategies such as venting to space and using water to wash down the LM proved to be somewhat effective. But this experience points out that vigilant housekeeping will be required, and as crew sizes and mission durations increase, this will become more of a challenge.

The important parameters for health effects include abrasion, reactivity (particularly in moist air and aqueous solutions) and the toxicological response.   Toxicological response is not straightforward to characterize as there is a wide variety of individual tolerances. Although it is clear that chemistry, size, shape, and activated surface states are important, exact correlations with toxicological response is not well understood.

6.2   About Building and Operating an Outpost

As helpful as the Apollo experience is, building and operating a lunar outpost will pose an entirely new set of challenges. Although the establishment of a continuously occupied facility will no doubt bring surprises, many of these can be anticipated, and mitigation measures employed.

6.2.1   Landing and Launch

For the first time multiple spacecraft will be landing and launching near existing mission assets such as habitation modules, rovers, and power plants. They probably will not be landing on prepared landing and launch pads, but on relatively wild terrain. Apollo did provide a single experience that is relevant. Apollo 12 landed about 160 meters from the Surveyor III spacecraft. Pieces from the Surveyor were removed and brought back to earth for further study. What was found was that all of the surfaces in line with the Apollo landing site were sandblasted with particles thrown up by the landing.[4] There were literally craters on the craters on the Surveyor surfaces. Subsequent analysis showed that some ~~fraction of the dust particles were~~fraction of the dust particles was traveling at a velocity sufficient to blast them into lunar orbit.[5]

6.2.2 Construction Activities

For the first time construction activities are being planned for the lunar surface. It is clear that portions of the regolith will need to be scraped, dug into, and drilled into. Projects may include the building of berms to protect the outpost from the blast of particles from launch and landing. It has also been suggested that lunar regolith be used as radiation shielding to protect astronauts from the radiation given off by solar storms. This would involve either digging trenches to place the habitats in or covering them with regolith. Roads will probably also be set out to connect the major structures in the outpost. This may be as simple as removing the larger rocks from the road areas, or as sophisticated as sintering together the regolith, perhaps with microwaves, to make smooth, paved roads.[6] But it is nearly certain than many tons of lunar regolith will need to be moved.

This means that such engineering properties as compressibility, shear strength, bearing capacity, slope stability, and trafficability must be determined for lunar regolith under lunar conditions. It is very challenging to determine these properties in ground tests. To determine reliable values for these properties a large amount of regolith (tons) would be required. This is not possible given the current quantities of regolith available, so these values must be determined using lunar simulants. Given the dependence of these properties on the particles size and shape distributions and the cohesion under lunar conditions, these properties are probably best probed by a combination of computer modeling and judiciously selected constraining experiments.

6.2.3 Power Generation

The lunar base will also consume much more power than the original Apollo missions. Apollo relied on fuel cells and batteries for their surface operations. But a lunar outpost will have power requirements on the same order of magnitude as the international space station. If solar cells are used to power the outpost, then some construction activity will be required to support them, as well as their associated radiators. This will probably involve the sinking of masts into the surface to suspend them from. If a nuclear reactor is chosen to power the outpost, then in all likelihood either the reactor would be buried in the regolith for radiation shielding, or berms or barriers would be built of regolith for the same purpose. Either way, large amounts of regolith must be excavated and moved. In this case radiators would be required as well, with again some sort of mast probably being required to support it.

With solar cells there is the problem of power losses due to dust obscuration. In addition, the power system will need to have radiators which will be subject to the constraints listed above. An additional problem that has received little attention is the excellent insulative properties of the lunar regolith. This means that there is no "Earth ground" to electrically tie scattered structures to. It has been suggested that it might be possible to establish a common grounding plane using plasma contactors to the solar wind plasma, though the feasibility of this approach has not been demonstrated.

6.3   About Utilizing the Moon's Resources
6.3.1   Mineral Mining

Any utilization of the Moon's resources starts with mining. The first step in the process is ore identification and selection. As an example, ilmenite might be a promising oxygen "ore" not because it contains far more oxygen than other minerals, but because less energy is required to extract oxygen from it than many other minerals. Most lunar mining will probably be in the form of strip mining, that is, scraping off the top portion of the regolith. This is because the top few cm are very loose, but the soil becomes quite compacted, just below that. Much less energy will be required to remove the top layers than those underneath it. In addition, this top layer is mostly finely ground through space weathering, making it easier to extract resources from than larger rock particles. But multi-ton quantities of regolith need to be moved, and the geotechnical properties of the regolith must be understood before construction equipment can be designed to dig through it working in vacuum at one-sixth gravity. Ideally, mining would be coordinated with construction activities. As an example the top layers of soil might be removed from a landing and launch pad, the oxygen extracted from the removed material, and the slag used to build up a berm around the pad.

Mining of ice from the permanently shadowed craters (if it exists), however, would probably be done quite differently. Most models suggest that the ice is covered by a layer of regolith, though that layer might be anything from mm to meters in depth. At any rate, the important resource would not be on the top, but buried. This would require digging much further into the regolith, perhaps even tens of meters, to retrieve the ice. In addition, this would be carried out at temperatures that might be as low as 40 K (about -390 °F).

6.3.2   Mineral Processing

After the ore is mined from the surface, it must be processed to extract the resource. After initial size sorting, and possibly grinding, some sort of beneficiation process will be used to sort the soil into component minerals by perhaps density, dielectric constant, magnetic susceptibility, or some other property. Fine particles will probably be suspended during this process, whether by falling or by using a fluidized bed.

One of the most important resources to be mined from the regolith might be adsorbed gases, particularly hydrogen and perhaps ^{3}He. Not only would schemes be required to recover the gases, but also to separate and store them, probably cryogenically.

After beneficiation, most processes will require that the regolith be heated, often to temperatures ranging 800 – 1800 °C. It will be important to understand the melting characteristics of the regolith, which will certainly be incongruent. Heating must occur in a controlled environment, which means sealing it off from the extraordinarily high vacuum of the moon. Since one of the major resources will be oxygen, once again there are issues recovering and storing it cryogenically. After the resource is extracted, the slag must be processed as well. The slag may well have important resources that could be harvested in subsequent steps, not the least of which is heat energy put in to extract the primary resource. As much of this as possible should be recovered to lessen the requirements to generate heat for mineral processing, which will probably be the largest energy consumer on the outpost. This may mean depositing it back into the mine, or transporting it to some other processing facility.

Since solar energy will probably be concentrated onto the ores to heat them up, thermal properties of the regolith such as the bulk specific heat, absorptivity, and emissivity will be required to design the reactors. Any number of properties such as the dielectric constant, magnetic susceptibility, or density maybe exploited for beneficiation of the regolith. The volatile content, as well as the adsorption binding properties will be important for the recovery of hydrogen and helium.

6.4 About Basic Regolith Properties

So from this wide range of activities and potential problems, what are the basic properties of the regolith that we need to understand, and replicate in a lunar simulant? The properties can be divided into two classes, properties that are dependant on the environment and those that are not.

6.4.1 Intrinsic Properties

Many of the particle properties are intrinsic, dependant only on the bulk chemistry and mineralogy of the particles. These include the grain density, dielectric constant, and thermal conductivity, as well as the hardness, radiation shielding effectiveness, melting behavior, magnetic susceptibility, absorptivity, and emissivity. Many of these properties have been measured and are available in resources such as the Lunar Sourcebook. That being said, as with any mineral there is a wide variety of compositional variants each with its own set of intrinsic properties. Great variations also exist in crystalline form, and in fact a large fraction of the regolith is not crystalline at all but glassy. In addition small amounts of minor constituents can drastically alter bulk properties.[7] The outstanding example in lunar regolith is the presence of nanophase metallic iron which has a large effect on the magnetic and dielectric behavior. It will be important, therefore, to understand the range of values of the intrinsic properties.

6.4.2 Granular Properties

In addition to the intrinsic properties the lunar regolith has granular properties. These include the distribution in size and shape of the grains. These have been extensively studied for regolith samples returned during Apollo and to a lesser extent Lunakhod. However, until recently the analysis only included particles larger than about 10 μm. The very fine fraction, which is only beginning to be studied, is critical for toxicology and perhaps other applications such as the degradation of thermal control surfaces. As noted ~~earlier~~earlier, it will be important to understand the variations in this fraction of the particle size distribution.

6.4.3 Environment dependent properties

There are two classes of environment-dependent properties of lunar regolith particles. The first class owes their environmental dependence to the fact that the regolith is a granular material. These include the bulk density, the bulk thermal conductivity, and the bulk dielectric constant. The second class owes their environmental dependence on their surface properties, and includes adhesion, cohesion, abrasion, and surface activation.

The granular material properties are going to vary with ~~high~~ how tightly packed the material is. For example, the bulk density for the top cm or so of regolith as about 1.0 g/cm^3, but down just 1 m increases to about 1.8 g/cm^3.[8] The bulk thermal conductivity differs significantly from the grain thermal conductivity because there are only point contacts between grains and there is no other coupling medium, such as air or water. Under these conditions the thermal conductivity is dominated by thermal radiation from grain to grain. Although the value will vary because of packing density and exact mineral composition, in general it is only about 1.5×10^{-3} W/m-K, as opposed to an average grain value of about 1.7 W/m-K. The bulk dielectric constant differs from the grain dielectric constant again because it is dominated by grain-to-grain contact. The

geotechnical properties, which will determine how difficult construction activities will be, are largely ~~dependant~~dependent on these bulk properties. To a first approximation, these properties can be simulated by a simple vacuum chamber, since the defining factor is the absence of material between the grains to transport the electric or thermal gradients. But in a simulant it is difficult to reproduce the interlocking character of the subsurface regolith.

The properties that are particle-surface-state dependent are difficult to even characterize on the lunar surface, let alone reproduce. This is because there is a better vacuum on the lunar surface than is attainable in the laboratory, and the lunar surface is under constant bombardment by high energy light and particles. The result is that the surfaces of regolith particles contain many activated sites, that is, atoms or lattice vacancies that are at high energy. These activated sites include free radicals, dangling bonds, and lattice defects. At a result, covalent bonds can form between particles in creasing their cohesion and adhesion. In addition, these activated sites have been associated with enhanced toxicity in silica on the earth.

These activated surfaces also greatly complicate the dust transport on the lunar surface since surface charges will interact in complex ways with the solar wind generated plasma on the lunar surface. As discussed above, these interactions are modulated by photo-charging of particles exposed to the direct solar ultraviolet, and so the mottled pattern of light and dark that will be particularly prominent in the polar regions, where the plans are to build the first outpost, complicated the analysis still further.

6.5   Conclusions

Understanding the wide range of impacts of the regolith on lunar missions is dependant on understanding the regolith properties. Central to this understanding is a clearer understanding of how dust will be transported on the moon, both by natural and anthropogenic effects. Dust transport on landing and launch is clearly the most important to develop an understanding given the potential for damage not only to the outpost but to orbiting spacecraft as well. Transport of the fine fraction this is clearly more complex than simple Newtonian mechanics. There is a complex interplay of a dynamic plasma environment with dynamically charging and discharging particles. Although the intrinsic and granular properties of the regolith have been the most thoroughly studied, key properties, such as adhesion, cohesion, abrasion, ~~geotechnic~~geotechnical properties, and toxicity are dependant on the environment and have not been well determined. With the complex matrix of materials, properties, and environments it is clear that all interactions will not be anticipated ahead of time. But the broad outlines of these interactions must be understood, and the details of how critical components of life support, power, and communications systems will interact with the regolith in the lunar environment must be studied in detail to reduce the risks to astronaut safety and mission success.

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